UNPUBLISHED PRELIMINARY DATA

COSMOLOGICAL IMPLICATIONS OF NEUTRINO EMISSION
BY PAIR ANNIHILATION IN MASSIVE STARS.

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THE IRON GROUP ELEMENTS AND THE EQUILIBRIUM PROCESS IN NUCLEOSYNTHESIS.

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I. INTRODUCTION

One of the most significant and interesting questions in astrophysics and cosmology at the present time concerns the number of neutrinos and anti-neutrinos emitted by a star during its evolutionary lifetime. The answer to this question depends in part on the universality of the so-called weak interactions. Is the coupling constant the same for all possible four-particle interactions between pairs of protons and neutrons, pairs of electrons and electron-neutrinos, and pairs of muons and muon-neutrinos or does the observed value only hold for those cases on which direct observations have been made, namely beta-decay, muon-decay, and muon capture?

Complete universality is implied by the conserved vector current theory of Feynman and Gell-Mann (1958a, 1958b). This theory has been shown to make correct predictions in a number of experimental tests by Bardin, Barnes, Fowler and Seeger (1960, 1962), Freeman, et al. (1962, 1964), Nordberg, Morinigo and Barnes (1960, 1962), Mayer-Kuckuk and Michel (1961, 1962) and Lee, Mo and Wu (1963), but the completeness of the universality was not directly in question in these experiments. Recent evidence for the existence of the parity violating characteristic of the weak interaction in interactions involving only nucleons has been given by Boehm and Kankeleit (1964) and by Abov, Krupchitsky and Oratovsky (1964) but the completion of further work by these authors and of completely independent tests such as those underway by Wäffler (1964) will be necessary before even this extension of the universality

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is accepted as valid. From an analysis of the isotopic abundances in the iron group elements on the basis of nucleosynthesis of these elements in an equilibrium process, Fowler (1962, 1963) and Fowler and Hoyle (1964) have suggested that there is strong circumstantial evidence for the emission of neutrinos and antineutrinos in electron-positron pair annihilation at just the rate predicted on the basis of the universality of the weak interaction. In Part II of this present paper this suggestion is reviewed and in Part III a brief discussion of the extent of neutrino emission by astronomical objects is given on the basis that this suggestion is correct.

II. NEUTRINO EMISSION DURING THE EQUILIBRIUM PROCESS

In massive stars in the range $10\ M_\odot < M < 50\ M_\odot$, Fowler and Hoyle (1964) show that nuclear evolution involving charged particle reactions proceeds from hydrogen burning via the CNO bi-cycle, through helium burning with the production primarily of oxygen, to oxygen burning with the production primarily of silicon. At the termination of oxygen burning, photodisintegration into alpha-particles with subsequent capture of these particles, the so-called $\underline{\alpha}$-process, leads to the synthesis of iron-group nuclei with mass number $A \sim 50$ to 60 which have the greatest binding energy and stability of all nuclear species.

These charged-particle reactions proceed primarily through nuclei which on the average have an equal number of neutrons and protons, $\overline{N} = \overline{Z}$. When the $\underline{\alpha}$-process comes to an end at $T_9 = T/10^9 = 3.5$, energy loss by neutrino emission leads to a mild contraction of the stellar core and a slight rise in temperature and density. At this point beta-processes, positron emission and electron capture, begin to play a role in the transformation to nuclei which have a greater number of neutrons than protons, e.g., Fe^{56}, and which are more stable than those with equal numbers, e.g., Ni^{56}.

The pertinent question is this. In the time scale permitted by the neutrino losses, how far will the beta-processes go in producing nuclei with a neutron excess? In other words, in the "equilibrium" or e-process in which the iron-group abundances are finally determined, does the material come to the complete equilibrium corresponding to the ambient temperature and density or does the limited reaction rate of the beta-processes impose an additional constraint? It has been emphasized by Burbidge, Burbidge, Fowler and Hoyle (1957) and Hoyle and Fowler (1960) that the abundances of the iron-group nuclei found in the solar system (particularly, terrestrial isotopic abundances) show definite effects of such a rate limitation. Figure 1 is adapted from B^2FH (1957) and shows the excellent agreement between observed iron-group abundances and those calculated for equilibrium at $T_9 = 3.8$.

It is assumed that solar-system iron-group nuclei are typical of nuclei produced in the e-process just outside the imploding central regions of Type II supernovae. These nuclei reside in the material which is swept out by the explosion of the mantle and envelope of the star. This explosion occurs in such a short time interval that the quasi-equilibrium abundances reached before the implosion-explosion are essentially unchanged. In what follows a most significant connection will be found between iron-group abundances and the time scale set by neutrino losses during the stellar stage just prior to core implosion and mantle-envelope explosion. The neutrino losses are taken to arise from the formation at high temperature of electron-positron pairs which can then annihilate with the production of neutrino-antineutrino pairs according to

$$e^+ + e^- \rightarrow \nu + \bar{\nu} \qquad (1)$$

This process follows straightforwardly from the conserved vector current theory of the weak interactions proposed by Feynman and Gell-Mann (1958a, 1958b).

The measure of beta-interaction rates appropriate for the present purposes is the rate of change of one-half the average neutron-proton difference per nucleus. This can be calculated from

$$\frac{1}{2}\frac{d(\bar{N}-\bar{Z})}{dt} = \frac{d\bar{N}}{dt} = -\frac{d\bar{Z}}{dt} = \frac{\Sigma \pm n(N,Z)/\tau(N,Z)}{\Sigma n(N,Z)} \quad , \qquad (2)$$

where $\bar{N} = \Sigma Nn(N,Z)/\Sigma n(N,Z)$, $\bar{Z} = \Sigma Zn(N,Z)/\Sigma n(N,Z)$, $n(N,Z)$ is the number of nuclei containing N neutrons and Z protons, and $\tau(N,Z)$ is the mean lifetime of these nuclei for beta-interactions. The positive sign is to be used for positron emission or electron capture and the negative sign for electron emission or positron capture. The problem at hand involves first of all the calculation of $n(N,Z)$ as a function of the ratio of protons to neutrons, $\bar{Z}/\bar{N}$. This is a task of considerable magnitude if temperature and density are also varied, and a computer program to accomplish the purpose has been undertaken by Clifford and Tayler (1964) at Cambridge University. Here we will fix on a temperature and density using some of their results and will discuss only in a general way what is essentially the "approach" to equilibrium in stellar nuclear processes.

Since B^2FH (1957) found that equilibrium calculations at $T_9 = 3.8$ gave excellent agreement with solar-system iron-group abundances, and since this temperature is just slightly above that at which the pure $\underline{\alpha}$-process ends, we will use this value in what follows. Then in a stellar core with effective mass $M_c = 20\ M_\odot$ FH (1964) show that $\rho_6 = \rho/10^6 = 3.1$, $N_e = 4.8 \times 10^{23}$ electrons and positrons per gm, $n_e = 1.50 \times 10^{30}$ electrons and positrons per cm^3,

$N_- = 3.9 \times 10^{23}$ electrons per gm, $n_- = 1.22 \times 10^{30}$ electrons per cm^3, $N_+ = 0.9 \times 10^{23}$ positrons per gm, and $n_+ = 0.28 \times 10^{30}$ positrons per cm^3. The electron-positron numbers will change slightly as Ni^{56} changes to Fe^{56} as the dominant nucleus during the operation of the e-process.

The termination of the α-process at $T_9 = 3.5$ followed by a slight rise in temperature and density upon contraction brings the material to $T_9 = 3.8$ with $\bar{Z}/\bar{N} = 1$ and Ni^{56} the most abundant nucleus. Beta-processes will now lower $\bar{Z}/\bar{N}$. For substitution in equation (2) one thus needs relative values for $n(N,Z)$ for a series of values for $\bar{Z}/\bar{N}$ at $T_9 = 3.8$. A fixed value for $\bar{Z}/\bar{N}$ serves as a constraint on the equilibrium process in the manner described by B^2FH (1957; see pp. 577, 578). Dr. Tayler and Mr. Clifford have carried out abundance calculations for $\bar{Z}/\bar{N} = 1.00$, 0.975, 0.950, 0.925, 0.900, 0.875, 0.8725, 0.870, 0.865, and 0.860 as part of their general program. The interval between successive values corresponds to $\Delta\bar{N} = 0.4$ neutrons per nucleus when $\Delta(\bar{Z}/\bar{N}) = 0.025$. A total change of ~2 neutrons per nucleus is thus covered as expected for the typical case ${}_{28}Ni^{56}_{28} \rightarrow {}_{26}Fe^{56}_{30}$. Table 1 lists the principal components of the material for various values of $\bar{Z}/\bar{N}$.

Methods for calculation of the $\tau(N,Z)$ under stellar conditions have been described by FH (1964). It will be clear that electron capture and positron emission are the important beta-processes since the trend in stability is toward nuclei with a neutron excess. Under terrestrial laboratory conditions positron emission is more rapid than electron capture if sufficient energy is available in the nuclear transformation to produce the positron rest mass and give the positron kinetic energy at least comparable to its rest-mass equivalent energy. However, in dense stellar interiors the electron density at the nucleus is considerably greater than in the undisturbed atom so that the rate

of electron capture is greatly enhanced. The result is that the proton-to-neutron change in radioactive nuclei which normally capture electrons or emit positrons is increased in rate and even stable nuclei, e.g., Ni^{58}, have fairly short lifetimes for capture of electrons having high energy in the tail of the thermal energy distribution.

Reference to Table 1 indicates that the nuclei which make important contributions in equation (2) are: Ni^{56} (2×10^3 sec), Ni^{57} (2×10^3 sec), Ni^{58} (5×10^4 sec), and Fe^{54} (4×10^4 sec). The proton (4×10^3 sec), Co^{55} (2×10^3 sec), and Fe^{55} (10^4 sec) also contribute. In general the transformation from $\overline{Z}/\overline{N} = 1.00$ to smaller values can be followed in Figure 2. At $\overline{Z}/\overline{N} = 1$ the principal constituents are Ni^{56}, Ni^{57}, and Co^{55}. These capture electrons or emit positrons to become Co^{56}, Co^{57}, and Fe^{55} respectively. The Co^{56} immediately becomes Fe^{54} and Ni^{58} through fast nuclear processes since $2\ Co^{56} \rightarrow Fe^{54} + Ni^{58} + 4.45$ MeV. Fe^{54} and Ni^{58} capture electrons to become Mn^{54} and Co^{58} which change by fast nuclear processes to Cr^{52}, Fe^{56}, and Ni^{60}. Fe^{55} and Co^{57} produce Mn^{55} and Fe^{57}. Eventually nuclear processes produce the equilibrium abundances which mainly reside in the stable nuclei which form the shaded "steps" in Figure 2, namely $Cr^{52,53,54}$, Mn^{55}, $Fe^{56,57,58}$, Co^{59}, and $Ni^{60,61,62}$ (the last two nuclei are not shown). Some material remains as stable Fe^{54} and Ni^{58} and also as stable Cr^{50} (not shown) and the other rare iron-group nuclei.

Table 1 gives the time intervals calculated using equation (2) for the changes through $\overline{Z}/\overline{N} = 1.00, 0.975, \ldots,$ to 0.860, and the total time to each value. Table 1 also gives the quantity $\theta = \log_{10} n_p/n_n$, the logarithm to the base 10 of the ratio of densities of free protons to free neutrons external to the complex nuclei. As pointed out by B^2FH (1957) equilibrium calculations

can be made quite simply using Θ as a parameter. It will be clear, however, that $\overline{Z}/\overline{N}$ is the more significant parameter. The computer program of Clifford and Tayler (1964) essentially finds the values of Θ which yield the chosen values of $\overline{Z}/\overline{N}$ and calculates the corresponding equilibrium abundances. It will be noted immediately that, as expected, very large ratios of free protons to free neutrons are required external to the complex nuclei to maintain the larger values for $\overline{Z}/\overline{N}$, e.g., $\Theta = 8.62$ for $\overline{Z}/\overline{N} = 1.00$. In simple physical terms a dense atmosphere of protons is necessary to prevent the nuclei with $Z = N$ from decaying to the more stable nuclei with $Z < N$. The electrostatic repulsion between protons in the nucleus which leads to increased stability for $Z < N$ is seen to have a powerful effect.

B^2FH (1957) found the optimum correspondence between solar system iron-group abundances and the calculated values for the case $T_9 = 3.8$ and $\Theta = 2.5$. We have already seen that $T_9 = 3.8$ is reached naturally in the stellar and nuclear evolution under discussion. The new calculations of Clifford and Tayler (1964) yield optimum results at $\Theta = 2.7$ which differs insignificantly from the B^2FH values. Correspondingly $\overline{Z}/\overline{N} = 0.872$ and $\frac{1}{2}\Delta(\overline{N}-\overline{Z}) \approx 2.0$ showing that the beta-processes changed approximately two neutrons into protons in the transformation from material with Ni^{56} the most abundant nucleus to material with Fe^{56} the most abundant.

The correspondence between the observations and the calculations of Clifford and Tayler (1964) is illustrated for the stable iron isotopes $Fe^{54,56,57,58}$ in Table 2. The solar-terrestrial values are those found first by dividing the iron abundance by mass by the abundance of all the equilibrium process elements (V, Cr, Mn, Fe, Co, Ni) using the <u>solar</u> spectroscopic data given by Aller (1961). The resulting value 73 per cent was then divided among the iron isotopes according to the <u>terrestrial</u> isotopic abundance ratios.

The chondritic iron abundance given by Suess and Urey (1956) is somewhat higher than the solar value. This higher value can be obtained from the equilibrium process calculations by employing a slightly lower value for the temperature without changing the isotope ratios significantly. The calculated values in Table 2 have been obtained from the abundances of Clifford and Tayler (1964) given in part in Table 1 by assigning all of the material at mass 56 to Fe^{56}, for example, on the basis that if the equilibrium process terminated at a given value for $\overline{Z}/\overline{N}$ then Ni^{56} and Co^{56} would subsequently decay to Fe^{56} and so forth.

The table shows that almost exact correspondence is obtained at $\overline{Z}/\overline{N}$ = 0.872 or $\theta = \log n_p/n_n = 2.7$ as noted previously. The time required for the electron captures up to this point is seen to be 3.2×10^4 sec. This value holds for a star of mass $M = 30\ M_\odot$ with core mass $M_c = 20\ M_\odot$ where $T_9 = 3.8$ and $\rho_6 = 3.1$ are the assumed equilibrium conditions. The mass $M = 30\ M_\odot$ is taken as typical of the range $10\ M_\odot < M < 50\ M_\odot$ for Type II supernovae. In the calculations positron emission, electron emission, and positron capture have been neglected relative to electron capture. At still lower $\overline{Z}/\overline{N}$, as complete equilibrium is attained, all processes, in particular positron capture, must be considered. The time required for the fast nuclear reactions to re-establish equilibrium as the electron captures take place has also been neglected. This is justified since, for example, the lifetime of Co^{56} to $Co^{56}(\gamma,n)Co^{55}$ - 10.07 MeV is $\sim 10^{-4}$ sec at $T_9 = 3.8$, $\rho_6 = 3.1$.

It will be noted that the time required for a given change in $\overline{Z}/\overline{N}$ or in $\frac{1}{2}(\overline{N}-\overline{Z})$ rapidly increases after $\overline{Z}/\overline{N}$ = 0.872. Table 1 shows that the change 0.875-0.850 requires more than ten times the interval required for the change 0.900-0.875. Table 2 shows that the total time from 1.000 to 0.850 is more than six times that required to reach 0.872. Thus we are in position [illegible]

an answer to the question posed in the third paragraph of this paper. In the time scale permitted by the neutrino losses, how far will the beta-processes go in producing nuclei with a neutron excess?

To answer this question it is necessary to compute the neutrino time scale under the conditions of temperature and density which have been reached in a star with $M = 30\ M_\odot$ when the beta-processes operate to change Ni^{56} and other $Z = N$ nuclei produced in the $\underline{\alpha}$-process to nuclei such as Fe^{56} with $\frac{1}{2}(N-Z) = 2$. In the Ni^{56}-Fe^{56} transformation the energy release is 6.6 MeV or 1.13×10^{17} erg gm^{-1} which is reduced to $\sim 10^{17}$ erg gm^{-1} by direct neutrino losses. At $T_9 = 3.8$ and $\rho_6 = 3.1$, FH (1964) show that $dU_\nu/dt \sim 10^{14}$ erg gm^{-1} sec^{-1} so the time scale is $t_\nu \sim 10^{17}/10^{14} \sim 1000$ sec ~ 17 min. This calculation underestimates t_ν. Some Ni^{56} begins to decay as soon as it is first produced at the beginning of the $\underline{\alpha}$-process. Thus an upper limit for t_ν is the sum of the interval for the $\underline{\alpha}$-process, which FH (1964) estimate to be 4000 sec, plus that for the Ni^{56}-Fe^{56} transformation. This sum is 4000 sec + 1000 sec = 5000 sec. The intermediate value, $t_\nu \sim 3000$ sec, is tentatively adopted.

The value just adopted tentatively holds for the time scale at the center of the star. Since the neutrino loss decreases rapidly with decreasing temperature the time scale will be somewhat longer throughout the central region in which the Ni^{56}-Fe^{56} transformation is taking place. Rough calculations lead to the final choice, $t_\nu \sim 6000$ sec. The Ni^{56}-Fe^{56} transformation is relatively insensitive to temperature, and no correction is necessary.

Thus we find $t_\nu \sim 6000$ sec is considerably shorter than $t_e \sim 3 \times 10^4$ sec. However, it must be recalled that these calculations have been made for a particular example, $M = 30\ M_\odot$, of the type of stars which HF (1960) suggested would evolve to become Type II supernovae, namely, stars for which

$10\ M_\odot < M < 50\ M_\odot$. The core mass was taken to be $M_c = (2/3)\ M = 20\ M_\odot$. Similar calculations for $M_c = (1/3)\ M$, which may be more realistic, show excellent correspondence between t_ν and t_e. In addition the lower range of stellar masses, $10\ M_\odot < M < 30\ M_\odot$, may well have contributed relatively more e-process material than the higher range, $30\ M_\odot < M < 50\ M_\odot$.

Thus, it would seem that quite close correspondence in the time scales exists for $e^- + e^+ \rightarrow \nu + \bar{\nu}$ and for $Ni^{56} + 2e^- \rightarrow Fe^{56} + 2\nu$ with a universal Fermi interaction for these two types of beta-interactions if the stars in which solar system e-process material was produced had masses 10-50 $M_\odot$ as originally contemplated by HF (1960).

The point under discussion here can be sharpened by a consideration of the time scale if $e^- + e^+ \rightarrow \nu + \bar{\nu}$ was not operative. Photon losses in the interval $3 < T_9 < 4$ can be estimated to be $\sim 10^7$ erg gm^{-1} sec^{-1} rather than the value $\sim 10^{14}$ erg gm^{-1} sec^{-1} for dU_ν/dt. Thus the photon-loss time scale for Ni^{56}-Fe^{56} is $\sim 6 \times 10^{10}$ sec $\sim$ 2000 years or ample time for the beta-interactions to reduce $\bar{Z}/\bar{N}$ well below the last values tabulated in Tables 1 and 2. The result, as shown in Table 2, would be, among other things, an enhancement in Fe^{58} and a decrease in Fe^{54} completely in variance with the terrestrial ratio. Clearly the time scale was not this long. Photon losses by the stellar material were not competent to decrease the time scale to the necessary value. On the other hand the neutrino time scale set by assigning the universal Fermi interaction strength to the process $e^+ + e^- \rightarrow \nu + \bar{\nu}$ in the pre-supernova stage of massive stars is closely that required to match the electron capture times involved in the formation of the Fe-isotopes and the other iron-group nuclei. The isotopic abundance ratios in any sample of terrestrial iron are circumstantial evidence for the universality of the beta-interactions.

This much can be asserted with some certainty: <u>The terrestrial iron group isotopic abundance ratios strongly indicate the operation in massive stars of an energy loss mechanism having a loss rate of the same order of magnitude as that calculated for</u> $e^+ + e^- \rightarrow \nu + \bar{\nu}$ <u>on the basis of the universal Fermi interaction strength</u>.

A comment on the ultimate values for $\bar{Z}/\bar{N}$ or $\Theta = \log n_p/n_n$ reached when the beta-interactions are in complete equilibrium is in order at this point. B^2FH (1957) estimated $\Theta = 1.4$ from a consideration of the equilibrium between free neutrons and free protons and electrons. This value is only an approximation at best. It does in principle cover the equilibrium between free protons and free neutrons and positrons. The difficulty involves the fact that neutrinos and antineutrinos escape and do not enter into reverse reactions once produced. This means, among other things, that energy must be supplied to maintain equilibrium at a given density and temperature. Granted this energy supply the equilibrium will depend more on the properties of the heavy nuclei than on those of the free neutrons and protons. The electron-positron ratio will be given as calculated by FH (1964) on the basis $\gamma \rightleftarrows e^+ + e^-$. Then when electron capture and positron emission are balanced exactly by positron capture and electron emission, equilibrium in the beta-interactions will have been reached. We found above that it was not necessary to carry the calculations this far. However, it is of considerable interest to know the value of Θ and $\bar{Z}/\bar{N}$ for the ultimate equilibrium. Calculations to determine these values are now being made by Clifford (1964).

The preceding analysis has been based on the assumption that a unique abundance distribution characteristic of a particular final value for $\bar{Z}/\bar{N}$ or Θ can match the observations reasonably well. However, it has also become

clear in the discussion that the value reached by $\overline{Z}/\overline{N}$ through beta-interactions depends on the time interval available for the e-process and thus on the mass of the pre-supernova stellar core. Hence, different abundance distributions are produced in supernovae of different masses and the solar system iron-group abundances represent an appropriate averaging over abundance distributions characteristic of a range of supernovae masses. We do not propose to carry out a detailed calculation along these lines at the present time but do wish to make some comments on the possibilities inherent in this line of attack.

Clifford and Tayler (1964) have confirmed the findings of B^2FH (1957) that the calculated results for θ near 2.7 yield too low values for the abundances of Cr^{50} and Ni^{58} by a factor of the order of 10. Averaging over a range of distributions characteristic of varying time scales may serve to correct this defect in the calculated results. Consider a mixed abundance distribution with contributions from low-mass supernovae (10-35 $M_\odot$) and from high-mass supernovae (35-50 $M_\odot$). The first contribution will dominate on the reasonable basis that the lower-mass stars are sufficiently greater in number such that a greater total mass has been processed in lower-mass supernovae than in those of higher mass. The major contribution will be characterized by a value for θ slightly lower than the unique value which gives the optimum fit as described above. Take $\overline{Z}/\overline{N} = 0.870$, $\theta = 2.48$, $\frac{1}{2}(\overline{N}/\overline{Z}) = 2.08$ as a possibility for this case. Then, for example, Fe^{58} will be somewhat greater than observed and Fe^{54} somewhat less.

Now dilute this abundance distribution with that from very massive supernovae ($\sim 10^3$ $M_\odot$) in which the time scale is not only too short for many beta-interactions to occur but is also too short for certain nuclear processes. As Ni^{56} decays to Co^{56} the nuclear processes will quickly convert the Co^{56} into the more stable nuclei having the same N-Z value, namely, 2. These are Cr^{50},

Fe^{54} and Ni^{58}. Zn^{62} with N-Z = 2 is not very stable and hence not very abundant at equilibrium. The conversion of the Co^{56} is mainly accomplished by the ejection of p and n from some Co^{56} nuclei and the addition of these p and n to others. As long as the numbers of free p and n are not changed this results in the mean molecular weight per nucleus remaining fixed at ~ 56. Actually equilibrium calculations indicate that n_p (free protons) tends to decrease through capture so that the mean atomic weight $\bar{A}$ tends to increase for this reason. On the other hand the light nuclei Si^{28}, S^{32}, Ar^{36}, Ca^{40} can serve as seed nuclei for the synthesis of new iron-group nuclei by capturing p,n,α and the mean molecular weight in the iron group might thus be changed. However, the equilibrium abundance of these nuclei is too small for this process to be effective.

New iron-group nuclei can also be made by the formation of C^{12} from three alpha-particles followed by subsequent p,n,α captures. Because of the low equilibrium density of alpha-particles this process will be infrequent on short time scale. Another possibility, but also much too infrequent to be effective, is the complete photodisintegration of Co^{56} nuclei into p,n,α with reassembly into nuclei which do not necessarily have mass number, A = 56. Given a long enough time scale this process does operate to decrease $\bar{A}$ below 56. It would seem that nuclear processes which will change $\bar{A}$ are too slow when t_ν becomes very short. Thus complete equilibrium will not be reached and the transformation of the Co^{56} must keep $\bar{A}$ = 56 or slightly increase it because of free proton capture. It will be clear that one Ni^{58} is needed for each Fe^{54} and three for each Cr^{50} if $\bar{A}$ remains fixed at 56, again neglecting Zn^{62}. As stated previously it can be reasonably expected that Ni^{58} and Fe^{54} will be the most abundant in the short time-scale distribution, with Cr^{50} enhanced over the abundance expected on a complete equilibrium calculation. Clearly the addition

of such a contribution will tend to remedy the deficiency in Cr^{50}, Ni^{58}, and Fe^{54} previously mentioned. This is borne out by the calculations in Table 1 for $\overline{Z}/\overline{N} = 0.925$ where complete nuclear equilibrium is assumed, but even so the results show considerable enhancement in Ni^{58} and Fe^{54}. Furthermore, the addition of some Ni^{56} which has not decayed but which eventually becomes Fe^{56} will restore the Fe^{58}/Fe^{56} ratio to a value close to that observed. In fact, this dilution improves practically all ratios since with the notable exceptions of Cr^{50}, Fe^{54}, and Ni^{58} the calculated ratios to Fe^{56} are in general high by ~ 50 per cent for $\theta = 2.48$. Rough calculations indicate that one part short time-scale distribution plus two parts long time-scale distribution will give improved agreement with the observations. Our basic conclusion previously reached is reinforced, but now it is necessary to postulate some e-process contribution from stars with M up to $\sim 10^3\ M_\odot$ as well as from $M \sim 10\text{-}50\ M_\odot$.

The discussion up to this point has primarily been concerned with a detailed comparison of the observed relative abundances of the Fe isotopes with equilibrium process calculations. Similar comparisons can be made for V, Cr, and Ni with similar results. The theoretical calculations will also yield the relative abundances of the various elements in the iron group by summing over the stable isotopes for each element. It is of interest to ascertain the ranges in temperature and density which will yield calculated values in fair correspondence with relative isotope abundances and then to compare the elemental abundances corresponding to this range in parameters with solar spectroscopic values and with meteoritic values.

It will be clear from the preceding discussion that it is advisable to exclude Cr^{50}, Fe^{54}, and Ni^{58} from the comparisons of theory with isotopic abundances since no attempt will be made to average over a range in time scales for the equilibrium process. Attention will thus be confined to $V^{50,51}$, $Cr^{52,53,54}$, Mn^{55}, $Fe^{56,57,58}$, Co^{59}, and $Ni^{60,61,62}$. (The rare isotope Ni^{64} is excluded since it has most certainly been produced in a neutron capture process subsequent to the equilibrium process.)

Table 3 lists percentage isotopic abundances (by number) for those isotopes of V, Cr, Fe and Ni which are under consideration. For each element the sum over the isotopes considered has been adjusted to 100 per cent. The second column contains the terrestrial values. The last five columns list values calculated by Clifford (1964) for a range of temperatures from $T_9 = 2.6$ to 3.9 and a range of densities from $\rho = 10^5$ to 10^7 gm cm^{-3}. For each ρ, T_9 combination, $\overline{Z}/\overline{N}$ was varied as in Table 1 and the calculated results in closest accord with the terrestrial observations have been tabulated. The small range in values for $\overline{Z}/\overline{N}$ in the five columns indicates that the time scale for the

process, as represented indirectly by this parameter, is the critical factor in the theoretical calculations. Inspection of the table indicates that the combination $T_9 = 3.0$, $\rho = 10^6$ yields the best results for V; $T_9 = 3.6$, $\rho = 10^6$ the best for Cr and Ni; $T_9 = 3.78$, $\rho = 3.1 \times 10^6$ the best for Fe. On the whole, $T_9 = 3.6$, $\rho = 10^6$ yields the closest correspondence with terrestrial values. This combination is somewhat superior to the B^2FH values, $T_9 = 3.78$, $\rho = 3.1 \times 10^6$. It would appear that the combinations $T_9 = 2.6$, $\rho = 10^5$ and $T_9 = 3.0$, $\rho = 10^6$ yield calculated values which deviate considerably from the terrestrial values.

Table 4 lists logarithmic abundance ratios (by number) for V, Cr. Mn, Co, and Ni relative to Fe. The first five rows below the column headings list calculated values corresponding to the ρ,T combinations of Table 3, while the last three rows list observations on the solar photosphere, the solar corona and meteorites for comparison. Since the theoretical calculations were made only for the isotopic species listed in Table 3 (plus Mn^{55} and Co^{59}) it was necessary to make the calculations for elemental abundances as follows. In the case of Cr, for example, the sum of the calculated values for Cr^{52}, Cr^{53} and Cr^{54} was multiplied by the terrestrial value for $[Cr]/[Cr^{52} + Cr^{53} + Cr^{54}]$. Similarly the terrestrial factor $[Fe]/[Fe^{56} + Fe^{57} + Fe^{58}]$ was employed in the iron abundance evaluation and then the calculation of log [Cr]/[Fe] led to the entry in Table 4. This procedure tacitly assumes that equilibrium process calculations will eventually give the relative abundances of Cr^{50}, Fe^{54} and Ni^{58} correctly and that relative isotope abundances are identical for all solar system material. This last assumption is known to hold for meteoritic and terrestrial iron group elements in those cases where meteoritic measurements have been made.

Before making a comparison of the theoretical calculations with the observational material, a comment on the latter is in order. It will be noted that the abundances listed for solar corona correspond very closely to the meteoritic values. It will also be noted that the tabulated solar photospheric abundances relative to iron are all higher by a factor from ~ 3 to ~ 5 than the coronal or meteoritic values. In other words iron appears relatively less abundant in the solar photosphere than in the solar corona or the meteorites. This discrepancy has been well known for some time and is a matter of some controversy. It is not our purpose to enter into this controversy but rather to let Table 4 speak for itself. It was indicated above that the combination $T_9 = 3.6$, $\rho = 10^6$ yields the closest correspondence with terrestrial isotope ratios. The elemental abundances calculated for this combination are in excellent agreement with the photospheric values for V, Mn and Ni relative to Fe but are too high by a factor of ~ 2.3 for Cr and too low by a factor ~ 2.5 for Co. In spite of the uncertainty associated with these factors it is apparent that the calculations support the low relative abundance for Fe reported for the solar photosphere rather than the higher relative abundance reported for the solar corona and meteorites. How this result is to be interpreted is a matter of considerable uncertainty at the present time. Clearly there is more observational work and analysis to be undertaken. Similarly equilibrium process calculations must be further refined and extended before a definitive comparison with improved observational material will be possible. This much can be stated with some emphasis. Eventually the relative element abundances in the sun and in unfractionated meteoritic material must be made consistent with terrestrial isotope ratios. Failing this, it will either be necessary to give up the concept of the equilibrium process or, alternatively, the assumption that all solar system material had the same nuclear origin.

III. IMPLICATIONS

Neutrinos and antineutrinos obey Fermi statistics and in an expanding universe they form a degenerate Fermi sea at very low energies. The effects of this universal Fermi degeneracy in various cosmologies has been discussed in detail by Weinberg (1962) and the reader is referred to this paper for the basic treatment of neutrino cosmology. Neutrino and antineutrino effects in astronomy and astrophysics have been most extensively discussed by Bahcall (1964 a,b,c,d) and by Bahcall and Frautschi (1964a,b). Here we will content ourselves with a discussion of the extent of neutrino and antineutrino emission by various astrophysical sources. Our discussion reviews and extends that given by Weinberg (1962) in Part IV of his paper. Our results will be expressed as the ratio of energy emitted as neutrinos or antineutrinos to the rest mass energy equivalent of the emitting system and are given in Table 5.

Nucleogenesis may occur through the creation of neutrons and antineutrons or through the creation of protons and antiprotons. In the former case beta decay probably occurs before other interactions but not, of course, in the latter case. In the former case the antineutrino or neutrino energy emitted is approximately 0.5 MeV or $\sim 5 \times 10^{-4}$ of the rest mass of the emitting particles.

Nucleosynthesis involving matter begins with the conversion of four protons into helium with the emission of two positrons and two neutrinos. The total energy emitted is 7×10^{-3} of the original rest mass; of this, 2% is emitted as neutrino energy in the pp-chain and 6% in the CNO bi-cycle. In the main-sequence and red-giant evolution of a star a minimum of one-tenth and a maximum of two-thirds of the hydrogen is converted into helium. An average value can be estimated on the basis that observationally one-third of the hydrogen of the Galaxy has been converted into helium. Taking all

of these factors into account it will be seen that to order of magnitude $\sim 10^{-4}$ of the rest mass energy is converted into neutrinos. A similar value holds for antineutrinos in nucleosynthesis involving antimatter.

Helium burning either to carbon via $3\ He^4 \rightarrow C^{12}$ or to oxygen via the additional reaction $C^{12} + He^4 \rightarrow O^{16} + \gamma$ does not involve neutrino or antineutrino emission directly. Furthermore helium burning takes place at such a low temperature that the pair annihilation process discussed in Part II is not operative even if the universal strength of the weak interactions applies.

Fowler and Hoyle (1964) show that helium burning results in carbon production in stars with $M < \sim 10\ M_\odot$ and in oxygen production in stars with $M > \sim 10\ M_\odot$. There is considerable uncertainty in the critical mass because the rate of the $C^{12}(\alpha,\gamma)O^{16}$ reaction has not yielded to experimental measurements to date and only approximate theoretical estimates can be made. Carbon burning results in the production of nuclei near Mg^{24} with little direct neutrino-antineutrino emission and takes place at too low a temperature for pair annihilation to be effective. Oxygen burning results in the production of nuclei near Si^{28} with little direct neutrino-antineutrino emission but does take place at high enough temperature ($> 2 \times 10^9$ degrees) for pair annihilation to be effective and to dissipate practically all of the nuclear energy if the universal strength of the weak interactions applies as suggested in Part II. The nuclear energy release is 5×10^{17} ergs gm^{-1} so the neutrino-antineutrino emission is $\sim 5 \times 10^{-4}$ of the rest mass. Subsequent to carbon or oxygen burning, the α- and e-processes occur in which heavier nuclei up to the iron group are produced. Pair annihilation is operative and again practically all of the available nuclear energy is radiated in the form of neutrinos and antineutrinos. The nuclear energy release is 3×10^{17} ergs gm^{-1} so that the neutrino-antineutrino energy emission is $\sim 3 \times 10^{-4}$ of the rest

mass. Thus in stars with $M < \sim 10\ M_\odot$ nucleosynthesis beyond hydrogen burning releases $\sim 3 \times 10^{-4}$ of the rest mass energy in neutrinos and antineutrinos while for $M > \sim 10\ M_\odot$ the total is $\sim 8 \times 10^{-4}$. However, in the smaller mass range a larger fraction, say one-third, of the mass is completely evolved to the nuclear end-point than in the larger mass range where a fraction more like one-eighth can be conveniently taken as a good average. Thus in both cases the overall result is that $\sim 10^{-4}$ of the total rest mass is emitted as neutrino-antineutrino energy. If we include hydrogen burning then in the full run of nuclear evolution in matter, $\sim 1.5 \times 10^{-4}$ of the rest mass energy appears as neutrinos, 0.5×10^{-4} as antineutrinos and 2×10^{-4} <u>in toto</u>. For nuclear evolution in antimatter the roles of neutrinos and antineutrinos are reversed. The arguments given in this paragraph are those used to justify the private communication referred to by Weinberg (1962) in footnote 9, page 1461.

We have so far neglected the neutron capture s- and r-processes by which the heavier elements beyond $A \sim 60$ are produced. On the basis of solar system element abundances only $\sim 10^{-6}$ of the original mass has been through the s-process. For the heavy nuclei averaged over abundances the mean atomic weight is $A \sim 75$. About twenty neutrons have been added to the typical seed nucleus but only about seven or eight of these have been converted into protons with the emission of an antineutrino so that one additional antineutrino per 10 nucleons is emitted in the s-process. The antineutrino energy is of the order of 2 MeV compared to the nucleon rest mass equivalent $\sim 10^3$ MeV so the overall factor for antineutrino emission in the s-process is $\sim 2 \times 10^{-10}$. For the r-process, the abundance is $\sim 2 \times 10^{-7}$ according to recent estimates but the antineutrino energy is of the order of 6 MeV so that the overall factor is $\sim 1 \times 10^{-10}$. It is thus clear that these processes can indeed be neglected in comparison to nucleosynthesis up to the iron group elements.

The above discussion follows conventional ideas concerning nuclear evolution in stars and galaxies. We now turn to new and somewhat more speculative ideas which have been mainly put forward in attempts to understand the strong radio sources discovered in radio astronomy and the ultra-luminous quasi-stellar objects which exhibit large optical red shifts.

According to Hoyle and Fowler (1963a, 1963b) and to Fowler (1964) the energy generation in the quasi-stellar objects can be understood in terms of hydrogen burning so that the neutrino emission factor is $\sim 10^{-4}$. We see no problem in meeting the energy requirements of the quasi-stellar objects, which we identify as massive stars with $M \sim 10^{8\pm1} M_{\odot}$, by means of the nuclear resources of the cores of these stars. There is a problem in the mechanism by which they are stabilized for periods as high as $\sim 10^{5}$ years. If spherically symmetric and non-rotating, the hydrostatic equilibrium of these stars requires large inputs of energy (Fowler, 1964 and Iben, 1963) and is unstable to general relativistic collapse (Fowler, 1964, Chandrasekhar, 1964a,b,c and Gratton, 1964). However, rotation and fragmentation (Hoyle and Fowler, 1963c) are two of numerous mechanisms which have been suggested as stabilizing agents.

The energy requirements for the strong radio emission from radio galaxies are so great according to some methods of calculation that Hoyle and Fowler (1963a, 1963b) pointed out that nuclear reactions in a galactic nucleus limited to less than 1% of the total mass would not suffice as the energy source. The release of gravitational energy during gravitational collapse was suggested as an alternative but serious difficulties arise in the energy emission cut-off due to the large red shifts which develop during collapse to the Schwarzschild limit. The problem is under extensive study in many places and until such a time as a solution is reached we are compelled to proceed on the basis of direct analysis of the observations. If the high energy electrons which yield

the radio synchrotron emission are produced in proton-proton collisions (Burbidge, 1962) then electron neutrinos and antineutrinos plus muon neutrinos and antineutrons are produced with roughly equal energies to that of the high energy electrons. Take 10^{44} ergs sec^{-1} as a representative rate of emission over a maximum time scale of 5×10^8 years (Minkowski, 1964) to obtain $\sim 10^{60}$ ergs for the energy emitted by the high energy electrons and assign a similar value to the high energy neutrinos of all types. On the grounds that the radio galaxies do not show evidence for spectacular violent events let us assume that at most 1% of the total mass, most probably in the galactic nucleus, was at one time involved in the energy production. Sandage (1964) has suggested that radio galaxies are probably quite massive of the order of 10^{12} $M_\odot$. Thus we take $\sim 0.01 \times 10^{12} \times 10^{54} \sim 10^{64}$ ergs as the energy equivalent of the mass involved. Again the value $\sim 10^{-4}$ is obtained for the neutrino energy relative to this energy but here there is considerably greater uncertainty to be attached to this value than even in our previous estimates.

A still more speculative estimate can be made if one considers the probability that the gravitational collapse of massive stars to the Schwarzschild limit occurs frequently with the result that a considerable fraction of the mass of a galaxy eventually becomes hidden or invisible in regard to the emission of any form of radiation but still produces a static gravitational field. Hoyle, Fowler, Burbidge and Burbidge (1964) showed that during the collapse of a massive star the loss of energy in the form of neutrino-antineutrino pairs produced by electron-positron annihilation was substantial even though not great enough to reduce the observable mass to zero at the Schwarzschild limit. Their expression for the fractional loss as a function of the initial rest mass of the star can be written as

$$\frac{E_\nu}{Mc^2} \sim 10^{-2} \left(\frac{M}{M_\odot}\right)^{\frac{3}{7}} \left[1 - 10^{-3} \left(\frac{M}{M_\odot}\right)^{\frac{27}{35}}\right]$$

This fractional loss reaches a maximum value ~ 0.15 for $M \sim 2 \times 10^3\ M_\odot$ and is equal to 0.06 at $M \sim 100\ M_\odot$ and to 2×10^{-4} at $M \sim 10^6\ M_\odot$. If one averages this loss over a reasonable number-mass law such as $N(M) \propto M^{-2.4}$ for all stars with $M > \sim M_\odot$ then it is found that the average loss is about 0.03. The problem now reduces to speculation concerning the possible amount of invisible mass in galaxies and in particular in the Galaxy. It does not seem possible that considerations of the dynamics of the Galaxy could rule out a value around one-third and using this value we come to $E_\nu/Mc^2 \sim 0.01$ for neutrino loss during the gravitational collapse of massive stars in galaxies. The estimate is admittedly quite speculative but it will be noted that it is the order of 100 times the value obtained during conventional stellar evolution or in the production of energy in radio sources. Furthermore it must be emphasized that even this result depends on the assumption that the weak interaction is universal and that the coupling constant measured in beta decay, muon decay and muon capture applies to the annihilation of electron-positron pairs with neutrino emission. Nevertheless the result indicates the possible great relevance of new neutrino processes in cosmology as theoretical and experimental research brings these new processes to light.

Weinberg's calculations show that on the basis of current ideas the degenerate neutrino sea will be observable, if at all, only in the oscillating cosmologies. However, his results serve to illustrate the main thesis of this paper. The mass density equivalent of the neutrino energy density is related to the Fermi energy, E_F, by the well-known expression

$$\rho_\nu = \frac{1}{8\pi^2}\left(\frac{E_F}{\hbar c}\right)^3 \frac{E_F}{c^2}$$

$$\sim 3 \times 10^{-21}\ E_F^4\ \text{gm cm}^{-3}$$

for E_F in eV. E_F can be measured by observations on the behavior near the end point of the energy spectrum in beta decay and present results set an upper limit, $E_F < 200$ eV. This corresponds to an upper limit, $\rho_\nu < 5 \times 10^{-12}$ gm cm^{-3}, which is $\sim 10^{18}$ times the nucleon rest mass density of 10^{-29} gm cm^{-3} required in steady state cosmology which in turn may be one or two orders of magnitude greater than that observed in luminous stars. Alternatively it will be noted that $E_F \sim 0.01$ eV if the "missing" mass-energy is indeed in the form of neutrinos. Clearly this low value is impossible to detect experimentally in terrestrial laboratories with present techniques. The experimental techniques in physics will certainly improve in the future but in the meantime observations of the cosmic neutrino flux must be pushed to the limit in astronomy. We do not argue from ignorance either in the sense of McVittie (1964) or Bondi (1964) but we do argue that forms of mass-energy which are difficult to detect cannot necessarily be ignored. Information about the universe is not transmitted by photons alone!

TABLE 1

THE APPROACH TO EQUILIBRIUM AT $T = 3.8 \times 10^9$, $\rho = 3.1 \times 10^6$, $M_c = 20\ M_\odot$, $M \approx 30\ M_\odot$

	$\frac{1}{2}(\bar{N}-\bar{Z})$	$\bar{Z}/\bar{N}$	$\log n_p/n_n$	TIME (10^4 sec)	
1	0.0	1.000	8.62		0.0
				0.1	
2	0.4	.975	7.36		0.1
				0.1	
3	0.8	.950	6.61		0.2
				0.2	
4	1.2	.925	5.18		0.4
				0.8	
5	1.6	.900	4.04		1.2
				1.6	
6	2.0	.875	2.94		2.8
				0.4	
7	2.04	.8725	2.74		3.2
				0.5	
8	2.08	.870	2.48		3.7
				18.0 { 1.3	
9	2.16	.865	1.76		5.0
				3.0	
10	2.24	.860	1.17		8.0
				12.8	
11	2.40	.850			20.8

(continued)

TABLE 1 (continued)

ABUNDANCE IN PERCENT BY MASS

(Naturally radioactive nuclei in parentheses)

NUCLEUS	(Co^{55})	(Ni^{56})	(Ni^{57})	Ni^{58}	Fe^{54}	(Fe^{55})	Fe^{56}	Fe^{57}	Fe^{58}
PRODUCT	(Fe^{55})Mn^{55}	(Co^{56})Fe^{56}	(Co^{57})Fe^{57}	(Co^{58})	(Mn^{54})	Mn^{55}	(Mn^{56})	--	--
ENERGY DIFF. (MEV)	3.46	2.10	3.24	-0.38	-0.69	0.23	-3.71	--	--
τ_{star} (SEC)	2×10^{3}	2×10^{3}	2×10^{3}	5×10^{4}	4×10^{4}	10^{4}	10^{8}	--	--
1	3.3	69.1	2.9	0.7	1.7	3×10^{-3}	6×10^{-5}	--	--
2	8.7	54.3	7.5	7.9	19.3	0.2	1×10^{-2}	--	--
3	8.2	21.4	6.8	16.7	43.4	0.9	0.1	--	--
4	2.1	1.0	1.5	18.5	60.1	6.0	4.1	2×10^{-3}	--
5	0.3	3×10^{-2}	0.2	8.3	34.0	12.0	29.2	6×10^{-2}	4×10^{-3}
6	2×10^{-2}	5×10^{-4}	9×10^{-3}	1.2	6.8	7.9	62.9	0.4	0.1
7	8×10^{-3}	2×10^{-4}	5×10^{-3}	0.8	4.7	6.7	66.2	0.5	0.2
8	4×10^{-3}	--	2×10^{-3}	0.4	2.8	5.3	69.2	0.7	0.3
9	4×10^{-4}	--	2×10^{-4}	0.1	0.6	2.5	70.5	1.5	1.2
10	--	--	--	2×10^{-2}	0.2	1.2	64.5	2.7	4.0

TABLE 2

IRON ISOTOPES

PER CENT OF TOTAL E-PROCESS ABUNDANCE BY MASS

$M_c = 20\ M_\odot,\ M \approx 30\ M_\odot$

$\bar{Z}/\bar{N}$	$\log n_p/n_n$	Fe^{54}	Fe^{56}	Fe^{57}	Fe^{58}	ELECTRON CAPTURE TIME (10^4 SEC)
1.000	8.6	1.7	89.1	2.9	0.0	0.0
0.950	6.6	43.4	21.9	7.2	0.0	0.2
0.900	4.0	34.0	29.6	4.7	0.04	1.2
0.872*	2.7	4.3	66.6	2.5	0.23	3.2
0.860	1.2	0.2	64.5	3.0	4.0	8.0
0.850	--	--	--	--	--	20.8
SOLAR-TERR VALUES		4.2	67.2	1.6	0.25	

* Interpolated from calculated values at 0.8725 and 0.870.

TABLE 3

PERC[illegible]E ISOTOPIC ABUNDANCES (BY NUMBER)

	TERRES[illegible] VAL[illegible]	CALCULATED				
T_9	--	2.6	3.0	3.6	3.78	3.9
ρ	--	10^5	10^6	10^6	3.1×10^6	10^7
$\overline{Z}/\overline{N}$	--	0.865	0.865	0.865	0.8725	0.867
V 50	0.24	0.08	0.28	0.90	0.88	1.34
V 51	99.76	99.92	99.72	99.10	99.13	98.67
Cr 52	87.53	97.67	95.96	90.58	82.16	85.10
Cr 53	9.98	1.06	2.50	6.77	16.08	11.79
Cr 54	2.49	1.27	1.54	2.65	1.76	3.11
Fe 56	97.32	98.25	97.73	95.94	96.01	95.14
Fe 57	2.33	0.51	1.09	2.72	3.69	3.80
Fe 58	0.35	1.24	1.18	1.34	0.30	1.06
Ni 60	84.40	79.37	84.86	86.42	96.90	89.60
Ni 61	3.83	0.84	1.71	3.78	1.53	4.33
Ni 62	11.78	19.80	13.43	9.81	1.57	6.06

TABLE 4

LOGARITHMIC ABUNDANCE RATIOS (BY NUMBER)

RELATIVE TO Fe

T_9	ρ	$\overline{Z}/\overline{N}$	V	Cr	Mn	Co	Ni
2.6	10^5	0.865	-4.29	-1.06	-2.44	-2.95	-0.91
3.0	10^6	0.865	-3.73	-0.96	-2.02	-2.59	-0.76
3.6	10^6	0.865	-2.93	-0.75	-1.50	-2.22	-0.68
3.78	3.1×10^6	0.8725	-2.87	-0.79	-1.01	-2.06	-0.54
3.9	10^7	0.867	-2.75	-0.75	-1.28	-2.05	-0.57
SOLAR PHOTOSPHERE Müller (1964)			-2.77	-1.11	-1.57	-1.83	-0.56*
SOLAR CORONA Pottasch (1964)				-1.81	-2.04	-2.26	-1.14
METEORITES Suess & Urey (1957)			-3.44	-1.89	-1.94	-2.53	-1.34

*Uncertain

TABLE 5

NEUTRINO ENERGY EMISSION

		NEUTRINO ENERGY/REST MASS ENERGY
NUCLEOGENESIS	$n \rightarrow p + e^- + \bar{\nu}$ $\bar{n} \rightarrow \bar{p} + e^+ + \nu$	$\sim 5 \times 10^{-4}$
NUCLEOSYNTHESIS		
HYDROGEN BURNING	$4p \rightarrow \alpha + 2e^+ + 2\nu$	$\sim 10^{-4}$
HELIUM BURNING	$3\ He^4 \rightarrow C^{12},\ 4\ He^4 \rightarrow O^{16}$	0
CARBON BURNING OR OXYGEN BURNING		
+ α- and e-PROCESSES	C^{12} or $O^{16} \rightarrow Fe^{56} + 2\nu$	$\sim 10^{-4}$
+ PAIR ANNIHILATION	$e^+ + e^- \rightarrow \nu + \bar{\nu}$	
NEUTRON s- and r-PROCESSES	$(A > 60)$	$\sim 3 \times 10^{-10}$
QUASI-STELLAR OBJECTS (HYDROGEN BURNING)		$\sim 10^{-4}$
RADIO GALAXIES*	$p + p \rightarrow p, n, \pi^{\pm}, \pi^{o}$ $\pi \rightarrow e^{\pm}, \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \gamma$	$\sim 10^{-4}$(?)
GEN. REL. COLLAPSE → INVISIBLE MASS	$M \sim 100\ M_\odot$	~ 0.06
$e^+ + e^- \rightarrow \nu + \bar{\nu}$	$M \sim 2 \times 10^3\ M_\odot$	~ 0.15
	$M \sim 10^6\ M_\odot$	$\sim 2 \times 10^{-4}$
	$N(M) \propto M^{-2.4}$	~ 0.03
	ONE-THIRD HIDDEN (MAX)	$\lesssim 0.01$

* Note that muon neutrinos and antineutrinos are emitted in this case and that high energy resonant scattering is possible for the electron neutrinos and antineutrinos (see references by Bahcall and by Bahcall and Frautschi).

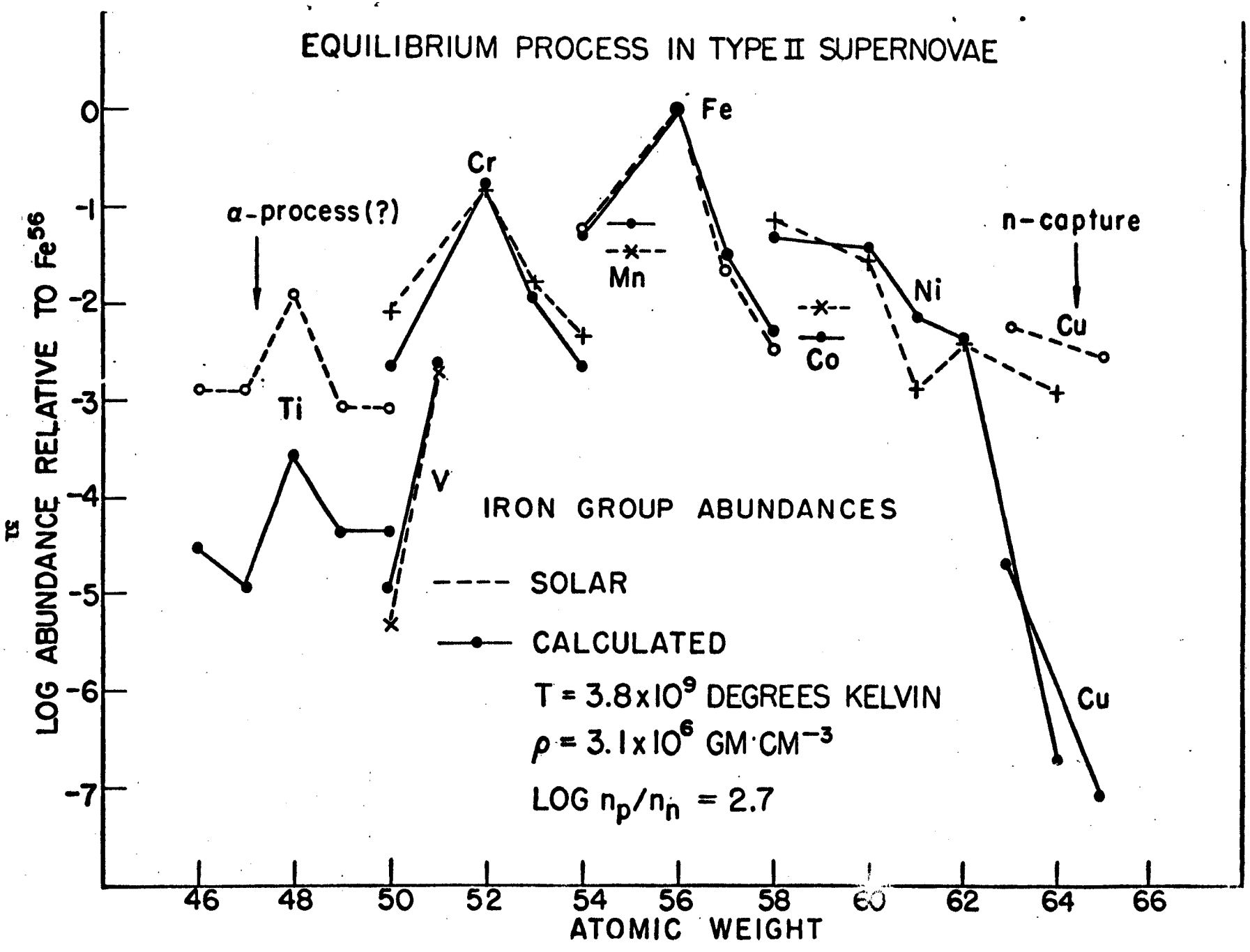

Fig. 1. The abundance relative to Fe^{56} of nuclei produced in the e-process.

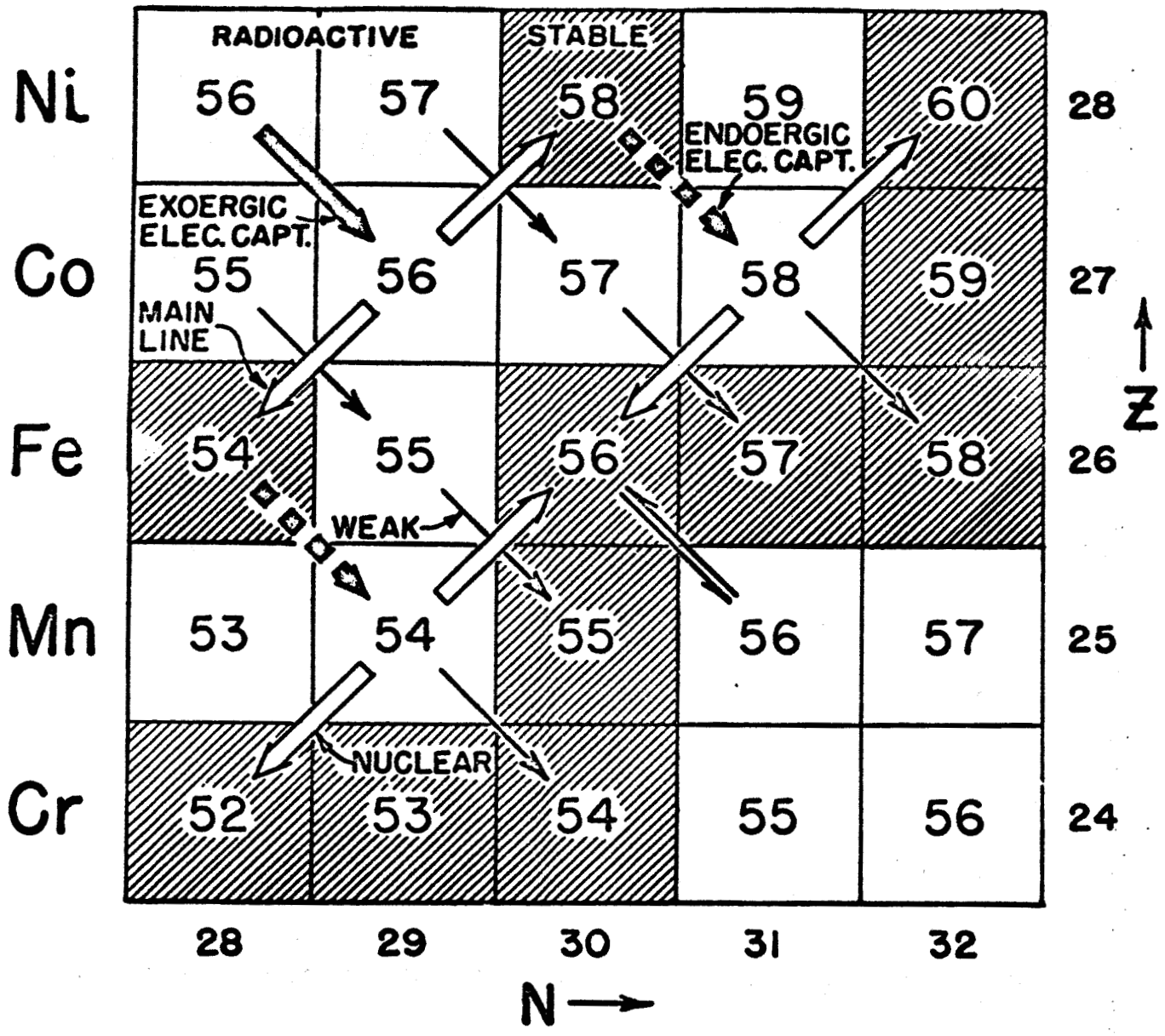

Fig. 2. The flow of nuclear material in the N,Z-plane during the equilibrium or e-process showing the effects of the slow beta interactions and the rapid nuclear interactions. The α-process results mainly in the production of Ni^{56} with about 10 per cent Co^{55}, Ni^{57}, Fe^{54}, and Fe^{52} (not shown).

REFERENCES

Abov, Yu. G., Krupchitsky, P. A. and Oratovsky, Yu. A. 1964, Congrès International de Physique Nucléaire, Paris.

Aller, L. H. 1961, The Abundance of the Elements (New York: Interscience Publishers).

Bahcall, J. N. 1964a, Phys. Rev. Letters, 12, 300.

_____ 1964b, Phys. Rev., 135, B137.

_____ 1964c, ibid, in publication.

_____ 1964d, Science, in publication.

Bahcall, J. N. and Frautschi, S. C. 1964a, Phys. Rev., 135, B788.

_____ 1964b, ibid, in publication.

Bardin, R. K., Barnes, C. A., Fowler, W. A. and Seeger, P. A. 1960, Phys. Rev. Letters, 5, 323.

_____ 1962, Phys. Rev., 127, 583.

Boehm, F. and Kankeleit, E. 1964, Congrès International de Physique Nucléaire, Paris.

Bondi, H. 1964, Proceedings of Padova Symposium on Cosmology.

Burbidge, G. R. 1962, Prog. Theoret. Phys. Japan, 27, 999.

Burbidge, E. M., Burbidge, G. R., Fowler, W. A. and Hoyle, F. 1957, Rev. Mod. Phys., 29, 547; referred to hereafter as B^2FH (1957).

Chandrasekhar, S., 1964a, Phys. Rev. Letters, 12, 114.

_____ 1964b, ibid, 12 (E), 437.

_____ 1964c, Ap. J., 140, 417.

Clifford, F. E. 1964, private communication.

Clifford, F. E. and Tayler, R. 1964, Memoirs R.A.S., in publication.

Feynman, R. P. and Gell-Mann, M. 1958a, Phys. Rev., 109, 193.

_____ 1958b, Proceedings of the Second United

Nations International Conference on the Peaceful Uses of Atomic Energy, Vol. 30, 1958 (Geneva: United Nations).

Fowler, W. A. 1962, Oral presentation at Herstmonceux Conference, April 17.

_____ 1963, Henry Norris Russell lecture to American Astronomical Society, at College, Alaska, July 23.

_____ 1964, Rev. Mod. Phys., 36, 545.

Fowler, W. A. and Hoyle, F. 1964, Ap. J. Suppl., 91, 1; referred to hereafter as FH (1964).

Freeman, J. M., Montague, J. H., West, D. and White, R. E. 1962, Physics Letters, 3, 136.

Freeman, J. M., Montague, J. H., Murray, G., White, R. E. and Burcham, W. E. 1964, Physics Letters, 8, 115.

Gratton, L. 1964, Proceedings of Padova Symposium on Cosmology.

Hoyle, F. and Fowler, W. A. 1960, Ap. J., 132, 565; referred to hereafter as HF (1960).

_____ 1963a, Mon. Not. Roy. Astr. Soc., 125, 169.

_____ 1963b, Nature, 197, 533.

_____ 1963c, Proceedings of the International Symposium on Gravitational Collapse and Other Topics in Relativistic Astrophysics, Dallas, December 16, 1963 (Chicago: University of Chicago Press).

Hoyle, F., Fowler, W. A., Burbidge, G. R. and Burbidge, E. M. 1964, Ap. J., 139, 909; referred to hereafter as HFB^2 (1964).

Iben, I. 1963, Ap. J., 138, 1090.

Lee, Y. K., Mo. L. W., and Wu, C-S. 1963, Phys. Rev. Letters, 10, 253.

Mayer-Kuckuk, T. and Michel, F. C. 1961, Phys. Rev. Letters, 7, 167.

_____ 1962, Phys. Rev., 127, 545.

McVittie, G. 1964, Proceedings of Padova Symposium on Cosmology.

Minkowski, R. 1964, Proceedings of Padova Symposium on Cosmology.

Müller, E. 1964, Reported at the IAU Symposium on Abundance Determination in Stellar Spectra, Utrecht.

Nordberg, M. E., Jr., Morinigo, F. B. and Barnes, C. A. 1960, Phys. Rev. Letters, 5, 321.

_____ 1962, Phys. Rev., 125, 321.

Pottasch, S. R. 1964, Annales d'Astrophysique, 7, 163.

Sandage, A. 1964, Proceedings of Padova Symposium on Cosmology.

Suess, H. E. and Urey, H. C. 1956, Rev. Mod. Phys., 28, 53.

Wäffler, H. 1964, private communication.

Weinberg, S. 1962, Phys. Rev., 128, 1457.